On the Possibility of Altering the Trajectories of Asteroids and Comets Using Plutonium Implantation

George Chapline and Michael Howard
Lawrence Livermore National Laboratory

It is pointed out that creation of a critical assembly by implantation of Pu239 inside an asteroid or comet could produce a substantial force on the asteroid or comet due to either explosive ejection or asymmetric sublimation of material off the surface of the asteroid or comet. This would allow one to make substantial changes in an asteroid's or comet's orbital elements using existing launch vehicles and spacecraft technology. It is particularly intriguing that recurrent sublimation induced by plutonium implantation could over a few months time deflect even kilometer-sized earth-intersecting objects enough to avoid the earth. For the more distant future nuclear-powered pulse jets might be a cost-effective way of altering the trajectories of asteroids and comets.

Introduction

A number of possible schemes for deflecting earth-intersecting asteroids and comets have been proposed. Indeed, a proliferation of ideas is desirable since one would like to have available a wide variety of options for dealing with such an emergency. For example, while using nuclear explosions is one obvious approach to interdiction, future bans on the production and maintenance of nuclear explosive devices may make it desirable to have other options available. In this note we would like to bring attention to the possibility of deflecting asteroids and comets by directly implanting plutonium in the body of the asteroid or comet using small spacecraft similar to the one used in the Clementine mission to the asteroid Geographos.

Given any material body and any subvolume of that body, there is a concentration of Pu239 in that subvolume such that the plutonium plus material will constitute a critical assembly. Furthermore, in some materials this critical assembly will be autocatalytic; i.e. the assembly will evolve with time in such a way that the effective neutron multiplication factor k increases with time. Instantaneous creation of an autocatalytic critical assembly would produce a rapid release of fission energy, and lead to a thermal explosion. It has been estimated [Bowman and Venneri 1995] that the energy release in such an explosion is a few tons per kilogram of plutonium. While this is less energy yield than can be attained with nuclear explosive devices, it is still a thousand times better than what can be achieved with high explosives. In materials where the critical assembly is not autocatalytic the energy release may or may not have an explosive character, depending on whether the initial critical assembly is supercritical or just barely critical, though in general it will also be transient. However, in the case of a non-autocatalytic assembly that is barely critical the energy release may be recurrent, leading to a significantly greater energy yield per kilogram of plutonium.

Implanted Critical Assemblies

One might question whether it is possible in practice to create a critical plutonium assembly inside the body of an asteroid or comet because implantation into an object using an "earth-penetrating" projectile arriving in a direction normal to the surface of the object requires that the projectile's velocity be subsonic with respect with respect to the object. On the other hand typical relative velocities between earth launched spacecraft and near earth objects will be supersonic. In order to prevent ejection of the material in a penetrating projectile back into space, the projectile would have to be incident at a very shallow angle. It is not obvious that this can be done in practice; however, assuming that a package containing several liters of plutonium can be injected into the comet or asteroid, one would have essentially instantaneously created a critical assembly.

In fact, recent calculations of the critical masses of Pu239 diluted with water and silicon dioxide [Fig. 1] suggest that implantation of a few hundred kilograms of Pu239 into a volume a couple of meters across would suffice for the creation of a critical assembly in a comet. We have carried out similar calculations for the case of a stony asteroid [Fig. 2], with the result that implantation of a few hundred kilos of Pu239 would suffice to create a critical assembly. Agreater amount of Pu239 is needed in this case because the iron in these asteroids acts as a neutron absorber. We have not yet investigated the case of nickel-iron asteroids, because apparently the amount of Pu239 that would be needed is very large and implantation would be problematical.

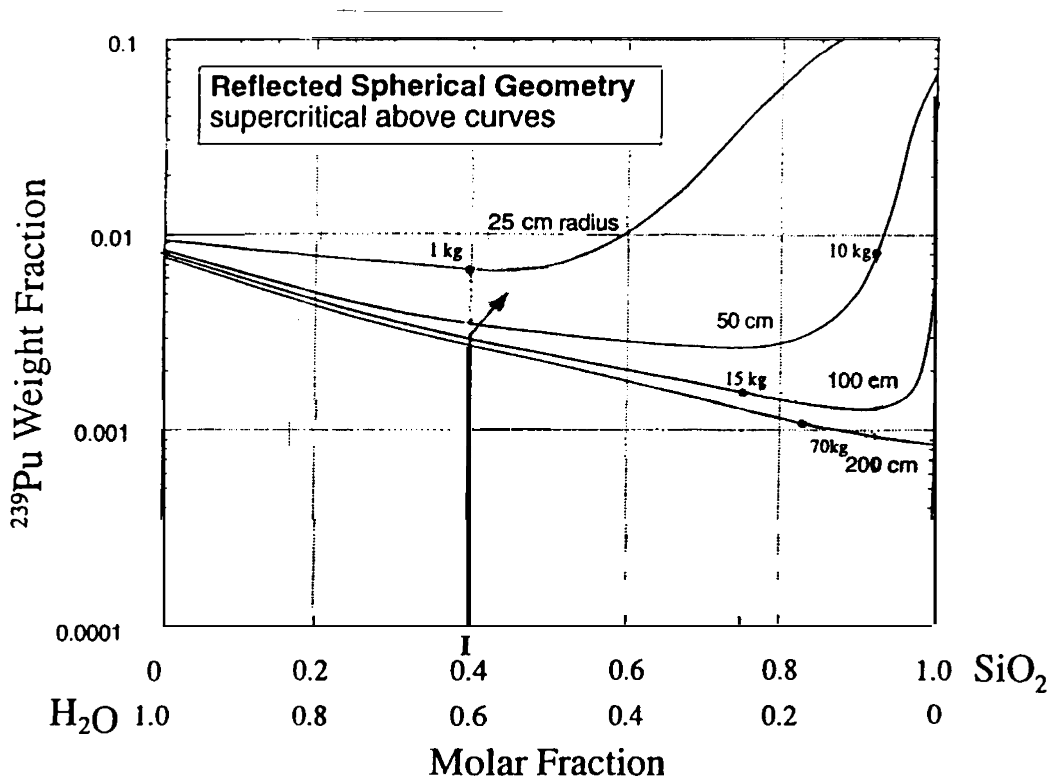

Figure 1. Criticality curves for spheres of Pu239 diluted with water and silicon dioxide and surrounded by silicon dioxide [Bowman and Venneri 1994]. The line "I" illustrates how a critical assembly can be created inside a comet by implantation of Pu239, and the arrow extending from the end of the line shows qualitatively how the resulting autocatalytic assembly would subsequently evolve.

Because the heat generated by the fissioning plutonium will cause the ice in a comet to vaporize and disperse, a critical assembly will tend to move to the right in Fig 1. If the initial critical assembly created by implantation lies on the left side of Fig 1, then the initial critical assembly will be autocatalytic; i.e. criticality will initially increase. Actually because the silicates in a comet are thought to be trapped in the ice as fine particles, the dispersing water vapor will probably also carry away much of the silicates, causing the critical assembly to evolve upwards as shown by the arrow in Fig1. Thus rapid implantation of Pu239 in a comet will most likely result in a situation wthere criticality will increase very rapidly, leading to a Chernobyl-like explosion.

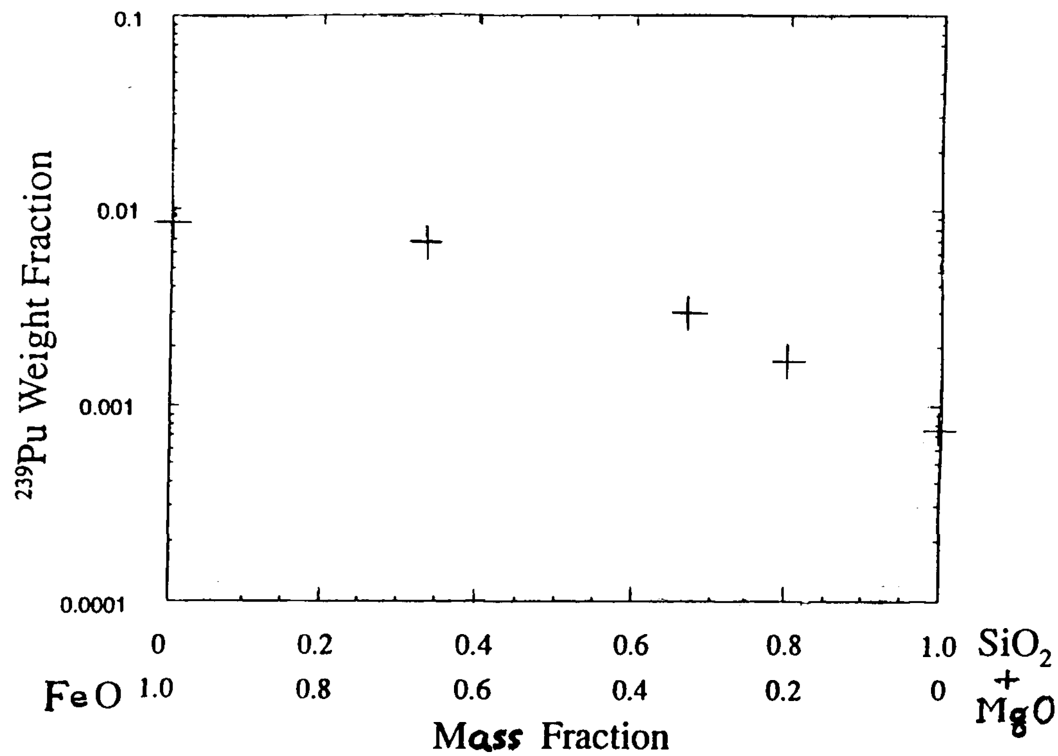

Figure 2. Criticality curve for a 2 meter radius sphere of Pu239 diluted with a mixture of iron oxide, magnesium oxide, and silicon dioxide and surrounded by silicon dioxide.

The explosive release of energy inside a comet or stony asteroid due to rapid implantation of plutonium could lead to ejection of fragments of the comet or asteroid. One would like the explosion to occur at a depth such that the velocity of ejection is as low as possible, since this would result in the greatest impulse. Unfortunately, the impulses that one can generate with a few hundred kilograms of plutonium are not very impressive, and would be only be useful for deflecting relatively small asteroids or comets. For example, let us assume that our autocatalytic or supercritical plutonium assembly yielded 250 tons, i.e. 1TJ, and the fragments were ejected with a velocity of 10 m/sec. Then making the optimistic assumption that 100% of the energy released appeared as kinetic energy of ejecta, the total impulse generated by the ejected fragments would be 200 billion Newton-seconds. This is clearly a gross overestimate of the impulse that would realistically be generated, yet even this impulse would be inadequate to produce desired deflections of any but the smallest asteroids or comets. For example, an impulse of 200 billion Newton-seconds would produce a transverse velocity of only 10 cm/sec or 3000 km/year in a kilometer-sized asteroid. Since the impulse generated varies inversely with velocity, a greater impulse might in principle be generated by lowering the velocity of the ejecta below 10 m/sec, but even this low a velocity would be difficult to achieve, since the fragmentation velocities associated with the explosive fracturing of rock are typically like 100 m/sec.

Sublimation Scenario

Fortunately, the picture for impulse generation brightens considerably if the critical assembly created by plutonium implantation can be operated in a regime where the energy generation is non-explosive, so that essentially all the energy goes into heating the surrounding material. If this heat is dissipated by sublimation of material off the surface of the comet or asteroid then a reaction force will be generated if the resulting momentum flow is not spherically symmetric. Now the interesting point is that if the energy generation is recurrent and uses up most of the plutonium, then the impulse generated by this asymmetric sublimation can be much larger than the impulse generated by explosive energy generation. If we assume that the velocities of the escaping molecules correspond to a temperature of roughly 0.1 eV, i.e. temperatures of about 1000C corresponding to escape velocities of about 400 m/sec, then the impulse generated by the consumption of 10 kg of plutonium would be on the order of a trillion Newton-seconds (note that sublimation occuring at lower temperatures would generate an even greater impulse). A trillion Newton-seconds is approximately the threshold impulse required to deflect kilometer-sized objects away from the earth in less than a year's time. In other words a critical plutonium assembly operating in a recurrent or quasi-steady state energy generation mode with an average power of several hundred megawatts could probably generate the desired deflection of a kilometer-sized object in a few month's time. Unfortunately a critical assembly producing a steady power of more than a hundred megawatts cannot be cooled by conduction alone. This level of average power production would require convection cooling, which means that the energy production could only be recurrent. Of course, if one had several years allowance in order to produce the deflection, then less power would be needed, and a critical assembly operating in a quasi- steady state mode might be adequate.

In order to ascertain approximately how much average power could be generated by implanting a given amount of Pu239, numerical simulations would have to be performed that simulated the implantation dynamics, as well as the relaxation processes that would be induced in the surrounding moderating material. Needless to say such numerical calculations would be very challenging, but the computational capabilities of the Los Alamos and Livermore Laboratories, as well as those of laboratories in the Soviet Union, could be profitably brought to bear on this problem. Obviously it would also be desirable to carry out experiments to check the numerical calculations, and demonstrate that a critical assembly operating at a desirable average power level could be actually be created by spacecraft implantation.

One obvious problem with the idea of using asymmetric sublimation to deflect asteroids or comets is that in general an unbalanced reaction force will not just deflect the asteroid or comet, but also cause it to rotate. Even in the presence of tumbling the deflection induced by a gigawatt of asymmetric sublimation will almost certainly be sufficient to avoid a collision with earth. Nevertheless it would be comforting if some means could be found to control tumbling. In principle this could be accomplished by implanting three independently controllable critical assemblies. However, this doesn't seem like a very practical proposal.

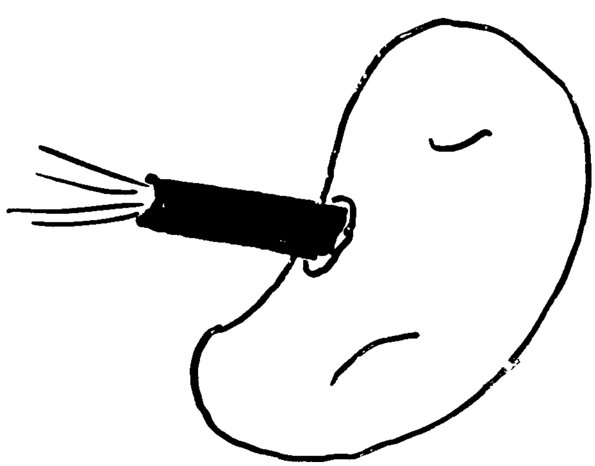

Figure 3. Nuclear pulse jet attached to an asteroid

Plutonium Powered Jet Engines

An elegant way of solving the tumbling problem would be to attach into the surface of the comet or asteroid a nuclear-powered jet whose position and orientation can be adjusted (Fig 3). The body of the comet or asteroid would provide a large reservoir of exhaust gas for the jet. In addition, the material of the comet or asteroid could be used as both a coolant and a moderator for pulsed nuclear power generation. For example, if the pulse jet reaction chamber incorporates a non-critical plutonium assembly, then a critical assembly might be formed by injecting material into the reaction chamber. If the critical assembly formed by this injection of material lies in a region of negative feedback (e.g. the right hand side of Fig 1), then the material will be gently heated and expelled from the reaction chamber. Evidently one would want to avoid forming an autocatalytic critical assembly, where the plutonium and injected material would be rapidly vaporized leading to an explosion. The reaction chamber should be designed so that the material in the reaction chamber is slowly heated, and after expulsion of the injected material from the reaction chamber the chain reaction will die out until more material from the asteroid or comet is injected.

Because of the typically large velocity differences between asteroids, comets, and the earth it would be nearly impossible to gently attach a nuclear jet (or anything else for that matter) to an asteroid or comet using existing chemical rockets. One may hope that in the future it will be possible to match the velocities of comets and asteroids relative to the earth using a high specific impulse nuclear rocket. Indeed development of nuclear rockets should be high on the list of technologies that one would want to develop for planetary defense. Not only would nuclear rockets allow one to approach asteroids and comets with a low relative velocity, but the transit time to these objects would be significantly reduced. Finally it should be be noted that the use of Pu239 in nuclear rockets for space exploration and in planetary defense schemes might be viewed as a socially responsible way of desposing of weapons grade plutonium.

Conclusion

Imparting an incremental velocity of 1 m/sec to a kilometer-sized object requires an enthalpy on the order of a TJ. Enthalpy yields of this magnitude can only be achieved in reasonable sized packages through the release of nuclear energy. Enthalpy from nuclear energy can be produced suddenly with a nuclear explosive device, or gradually with a nuclear reactor. Gradual release of heat in a nuclear reactor has the advantage that one may have more control over the consequences of the energy release, so the results achieved per unit of nuclear fuel used may be greater. Production of heat using a nuclear reactor is also desirable from the point of view that international agreements may in the future make it very difficult to build reliable nuclear explosive devices. One might have imagined that nuclear reactors are disadvantaged with respect to nuclear explosive devices because they are much heavier. However we have argued that by making use of the natural moderating and cooling properties of the in situ material of a comet or asteroid nuclear reactors are not disadvantaged with respect to nuclear explosive devices. Indeed it may be possible to gradually release energies on the order of a TJ inside an asteroid or comet simply by implanting inside the object a package containing plutonium that is subcritical before impact, but becomes critical after implantation by virtue of the environment.

Reference

Bowman, C. D., and Venneri, F., *Underground Autocatalytic Criticality from Plutonium*, Los Alamos National Laboratory, Los Alamos, NM, LA-UR 94-4022 (1994).